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To: Mr. G.O. Davidson
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WINGHAM - WAVEFORM DISTORTION

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Tests were performed in order to confirm the source of voltage distortion on the CKNX ac supply waveform and to assess the severity of this distortion. Voltage and current were measured at the metering unit of Western Foundry, the suspected source of the problem. The voltage was concurrently measured on the CKNX ac supply. The total harmonic distortion of the voltage waveform measured at Western Foundry is within the 3% Ontario Hydro limit. The balanced I.T, a measure of the inductive influence of the current distortion exceeds the accepted limit of 5 kA. Western Foundry contributes to the voltage distortion experienced by CKNX. The total harmonic distortion is, nevertheless, less than acceptable levels.

1.0 INTRODUCTION

CKNX Broadcasting operate an AM/FM/TV broadcasting station in Wingham, Ontario. They are presently experiencing interference to the audio portion of each of these broadcast services. This is a recent problem. It was first brought to the attention of the DOC on May 27, 1986. In response to their complaint the DOC investigated this problem and traced the interference to waveform distortion on the CKNX 60 Hz ac supply/1/. The distortion was visible as short duration decaying oscillations on the voltage waveform which coincided with audible buzz on the monitored audio of the AM/FM and TV transmissions.

Western Foundry operate a metal melting operation using induction furnaces with a peak load of about 9 MW. Sometime in May 1986, induction furnace No 6 was put into service. This is a 3.6 MVA Brown Boveri Corporation SCR controlled unit. Western Foundry is fed at 44 kV from the M6 feeder out of Wingham TS. CKNX is supplied from MS #1 which taps off the M6 and is only a few kilometers from Western Foundry.

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On June 24, 1986 Regional staff and Head Office staff together with the DOC, met first at CKNX and later at Western Foundry to investigate the problem. Preliminary information indicated a strong correlation between interference observed at CKNX between 11:32 and 11:49 am and the operation of Western Foundry's furnace No 6 as indicated by the operator's morning log.

Electrical Research was requested by Georgian Bay Region, Operations and Distribution Systems to perform appropriate measurements to confirm the source of interference and assess the severity of the waveform distortion on the ac supply/2/. Tests were performed on June 7, 1986 with the full cooperation of CKNX and Western Foundry staff with the assistance of Head Office, Walkerton Area lines and P&C staff. This report summarizes the test results.

2.0 SUMMARY OF TESTS

Tests performed on July 7, 1986 consisted of voltage distortion measurements at both Western Foundry and CKNX Broadcasting.

Measurements at Western Foundry were performed from the Research Division's mobile test facility. Cables were drawn from the metering unit in the control room to the van. Three phase voltage signals were conditioned using 30:1 isolation transformers connected Δ-Y. Red and blue phase currents were measured through 0.1Ω non-inductive shunts. Harmonic analysis was performed using the HP 3582A Spectrum Analyzer. The HP 3582A uses digital processing techniques implementing the Fast Fourier Transform (FFT). Each measurement consists of 32 RMS averages using the Hanning window. An HP 9826 microcomputer is used to control the analyzer, store the digital data on an internal floppy disk for analysis. An interactive user program is loaded from floppy disk. Measurements of each voltage and current quantity were done sequentially. One set of measurements took about 5 minutes. A Tektronix 468 digital storage scope was used to record the real time waveforms.

Measurements at CKNX Broadcasting were performed in the equipment room. The 120 volt ac supply waveform was measured at the same point as that being monitored by the CKNX staff. This was from an ac power bar at the rear of the CKNX equipment rack. A 10 X probe was being used by CKNX to monitor the ac waveform on their Tektronix 549 scope. Research Division instrumentation, connected to the same point included an HP 3562A Dynamic Signal Analyzer and a Nicolet 320 digital scope. Harmonic analysis of the voltage waveform was performed by the HP 3562A. Each measurement is the result of 32 RMS averages using a flat top window and the digital data is stored directly to a 3-1/2 inch disk drive. The HP 3562A calculates the Total Harmonic Distortion (THD) on the first 20 harmonics. Spectra were also obtained up to 10 kHz to observe trends with changes in Western Foundry's load. The Nicolet scope was used to observe the real time waveform and store the digitized signal in bubble memory. The results later showed that the stored trace of the supply waveform was less than 120 volts. The reason was not satisfactorily resolved but it appeared to be that our equipment loaded down the measurement point. The shape of the waveforms and the harmonic spectra are nevertheless valid as are the THD calculations which are relative measurements.

The load cycles of the SCR controlled furnace No 6 at Western Foundry were changed specifically for the tests over a short period in the afternoon between 15:00 and 15:40. The tests were performed in sequence during a "melt cycle", "off" cycle, "hold" cycle and a second "melt" cycle. Timing for the measurements at each test location was coordinated over a communications link consisting of UHF radio from the Western Foundry control room to the equipment van and from there by the telephone, supplied by Western Foundry, to the CKNX equipment room.

3.0 WAVEFORM DISTORTION

3.1 Harmonic Distortion

The SCR controlled unit at Western Foundry is a non-linear device and in the process of converting the ac to dc, changes the sinusoidal nature of the ac supply current. This generates harmonic currents which flow into the power systems resulting in harmonic voltage drops. The harmonic currents can result in inductive interference to communications circuits and can cause problems with various power system components. For this reason it is necessary to control the amount of allowable harmonic distortion on power systems waveforms.

3.2 Line Voltage Notches

During the operation of a three-phase full-wave converter, the thyristors operate in pairs to convert three-phase ac to dc by switching the load among the thyristor pairs 6 times per cycle. During this commutation process, there is a brief short-circuit between the two phases which produces a notch in the voltage waveform. These notches can excite the natural resonance of the power distribution system in the audio frequency range (15 to 20,000 Hz)/3/.

4.0 ACCEPTABLE LIMITS

4.1 Voltage Distortion

The Ontario Hydro limit for voltage distortion on the DES is 3% on a general feeder and 5% on a dedicated feeder/4/.

4.2 Telephone Influence Factor

The Ontario Hydro limit for balanced I.T is 5000 A and the limit for residual I.T is 250 A/4/.

4.3 Line Voltage Notch

Ontario Hydro does not presently stipulate limits on line notching.

5.0 TEST RESULTS

5.1 Waveforms

Examples of the voltage and current waveforms at Western Foundry are shown in Figure 1 a) b) c) for "off", "hold" and "melt" cycles of furnace No 6. Line notching pulses are evident in the "hold" and "melt" cycles and are clearly more severe in the "hold" cycle. The current waveforms show significant distortion under all load conditions.

Corresponding voltage waveforms at CKNX are given in Figures 2 to 4. The line notching pulses are only seen clearly on the "hold" cycle.

5.2 Harmonic Distortion

Table 1 summarizes the results of distortion measurements at Western Foundry and CKNX. The total harmonic distortion (THD) is calculated as:

$$THD = \frac{\left(\sum_{h=2}^{H} V_h^2 \right)^{1/2}}{V_1} \times 100\%$$

where V_h is the harmonic voltage
V_1 is the fundamental voltage
h is the harmonic order.

At Western Foundry the voltage distortion was calculated using the harmonic voltages derived from the spectrum analysis of the voltage waveforms from 0-5000 Hz using data from the HP 3582A.

At CKNX, the HP 3562A automatically calculates the THD on the first 20 harmonics (up to 1260 Hz). The harmonic spectra of the voltage waveforms at CKNX are shown in Figures 5 and 6. They show the presence of higher order harmonics during the "melt" and "hold" cycles compared to the "off" cycle. However, these higher order harmonics do not significantly affect the THD. Manual calculation including harmonics up to 10 kHz showed an increase in THD of less than 0.1%.

5.3 Telephone Influence Factor

The inductive influence is a measure of the potential interfering effect of the harmonics due to induction into nearby telephone circuits. It is generally given in terms of the I.T product of current (I) and the Telephone Influence Factor (TIF). The TIF is a dimensionless quantity and weights each harmonic current. It takes into account C-message weighting (based on the sensitivity of the ear and the telephone response characteristics) and the coupling between the power and telephone circuits, assumed to be proportional to frequency. The balanced I.T uses balanced phase currents.

The I.T product is calculated as follows:

$$I.T = \left[\left(\sum_{h=1}^{H} (I_h \times W_h)^2 \right)^{1/2} \right]^{1/2}$$

where W_h = 1960 TIF values
I_h = rms value of harmonic current
h = harmonic order

At Western Foundry the I.T products were calculated using the harmonic levels derived from the spectrum analysis of the current waveforms from 0-5000 Hz using data from the HP 3582A. The results are given in Table 1.

Table 1

Waveform Distortion

Load Cycle of Furnace #6	Time of Test	Measurement performed at: Western Foundry Metering Unit			CKNX 120 volt supply
		phase	I.T (kA)	THD (%)	THD (%)
"melt" cycle	15:11	r	11.3	1.6	1.5
	to	w	-	1.4	
	15:17	b	10.5	1.1	
"off" cycle	15:17	r	0.9	0.6	1.6
	to	w	-	0.5	
	15:22	b	1.3	0.3	
"hold" cycle	15:26	r	10.3	1.6	1.1
	to	w	-	1.4	
	15:30	b	9.1	1.3	
"melt" cycle	15:35	r	10.3	1.6	1.5
	to	w	-	1.6	
	15:39	b	11.6	1.5	

5.4 Interference to CKNX

The balanced I.T measured at the Western Foundry metering unit exceeds the Ontario Hydro limit of 5 kA during the operation of furnace No 6 in the "hold" and "melt" cycles. This means that the inductive influence of the harmonic currents flowing in the power system supply feeder may result in interference to a telephone exposure.

However, because the interference would appear to be related to the supply voltage distortion locally coupled into the disturbed equipment, the I.T limit does not directly apply to the interference being experienced at CKNX.

The I.T is essentially the same at Western Foundry on the "melt" and "hold" cycles whereas the interference was apparent only during "hold". This suggests that the interference is not directly related to the line current.

During the test sequence, line notching was observed only during the "hold" cycle (see figures 2 to 4). During this time an audio buzz was heard as pointed out by the CKNX staff monitoring the AM musical broadcast at that time. A buzz was clearly evident. During a subsequent microphone broadcast no interference was heard. Interference was not heard during other test sequences; however, it isn't clear whether the audio monitor was turned up at these times.

Comparison of harmonic spectra of CKNX supply voltage waveforms in figures 5 and 6 indicate that harmonics are generated over the audio frequency range during the "hold" and "melt" cycles. The "hold" cycle exhibits higher amplitude harmonics than the "melt" cycle in the higher order, odd and even harmonics. However, the THD during the "melt" cycle is higher than the "hold"

cycle. This is due to a higher 7th harmonic that dominates the THD calculation. Although there are many higher order harmonics they are substantially lower in magnitude and contribute little to the overall THD.

The THD is essentially the same on all load cycles at Western Foundry but the interference was observed on the "hold" cycle only. This suggests that the problem is not due to the lower order harmonics which dominate the calculation of the THD.

The audible buzz was heard only when the line notching was visible on the waveform. This occurred only on the "hold" cycle during the testing. These oscillating pulses can occur up to 6 times per cycle, spaced 30 degrees apart for a 3 phase full wave converter. Only four are clearly evident on the waveforms. This would give an audible buzz of about 240-360 Hz. Measured amplitude and period of an oscillation, using an expanded display of the stored data from the Nicolet digital scope show that the maximum p-p voltage of the decaying oscillation is approximately 4.5% at a ringing frequency of about 4700 Hz.

The source of the audible interference would appear to be distortion on the supply voltage waveform being coupled locally into the CKNX baseband audio circuits. The noise would appear to be electromagnetically coupled to the disturbed equipment but coupling through the dc supply although less likely, cannot be ruled out especially since several different pieces of equipment are involved.

The source of the distortion could be either the harmonics in the audible range or the line notching pulses.

The total harmonic distortion of the voltage waveform is well within the stipulated 3% limit. There is no allowable limit stipulated for the disturbance caused by line notching.

6.0 SUMMARY OF RESULTS

6.1 The voltage distortion (THD) at the metering unit of Western Foundry was between 1 and 1.6% under the "melt" and "hold" cycles of furnace No 6. This is well within the 3% limit on the DES for a general feeder. During the "off" cycle the THD was about 0.5%.

6.2 The voltage distortion (THD) at CKNX Broadcasting on a 120 volt ac outlet was 1.5 to 1.7% under all load cycles of furnace No 6 at Western Foundry. These are acceptable levels.

6.3 The balanced I.T of 10 to 13 kA measured during the melt and hold cycles exceeds the acceptable limit of 5 kA. During the "off" cycle the balanced I.T was about 1 kA which is an acceptable figure.

6.4 Line notching pulses are evident in CKNX waveforms during the "hold" cycle at Western Foundry. Audio interference to CKNX audio equipment was observed during this time.

6.5 Harmonic content of the CKNX voltage waveform is clearly higher during the "melt" and "hold" cycles than the "off" cycle over the audio portion of the spectrum. The waveform during the "hold" cycle exhibits the highest harmonic content.

7.0 COURSE OF ACTION

The supply authority has the responsibility to restrict the allowable distortion on the power system in order to provide a reasonably "clean" waveform to all customers. This responsibility is passed on to the customer installing non-linear equipment to meet specified limits of distortion at the point of common coupling.

Customers experiencing interference also have a certain responsibility to provide a reasonable amount of immunity in their equipment to interference sources. This may require special measures or simply involve good engineering practice.

In assigning responsibility it is important to keep in mind that there should not be an undue financial penalty passed on to any of the parties.

An appropriate course of action in this problem is not clear. The difficulty arises from the following:

- the voltage distortion is well within stipulated acceptable limits.
- the current limit given by the balanced I.T does not directly apply to the resulting interference.
- there is no limit on the line notching and it is not clear whether these disturbances exceed reasonable levels.
- it has not been established whether the interference at CKNX is not at least partly due to a problem with their own equipment or wiring and even their own ac supply arrangement.

Examination of possible remedial measures is not within the scope of this report. In general terms mitigation may involve reducing the disturbance or reducing the coupling. Reducing the disturbance can be done at the source of the disturbance or at the point of disturbance. High filtering costs will be incurred at the source because of the high power requirements for filter components. The costs will be lower at the point of interference because of the less stringent requirements for components. Costs to reduce the coupling are difficult to assess. A detailed study of the coupling mechanism and equipment susceptibility at CKNX would be required.

8.0 CONCLUSIONS

There is a strong correlation between the operation of Western Foundry's SCR controlled furnace No 6 and the voltage and current waveform distortion observed at the Western Foundry metering unit and the corresponding voltage disturbances at CKNX.

There is reasonable evidence that the audio disturbance heard on the CKNX equipment is due to these same disturbances coupled locally from the ac supply.

Tests were not performed to determine the mechanism of coupling between the ac supply disturbances and the CKNX equipment. This was beyond the scope of the investigation. It would involve a much greater effort considering the number of equipments apparently affected.

9.0 ACKNOWLEDGEMENT

I wish to thank both CKNX and Western Foundry staff for their full cooperation during the tests. My appreciation is also extended to D. Jendek, W. Mogk, J. Ekensweiler and B. Pietrantonio for their assistance.

Submitted

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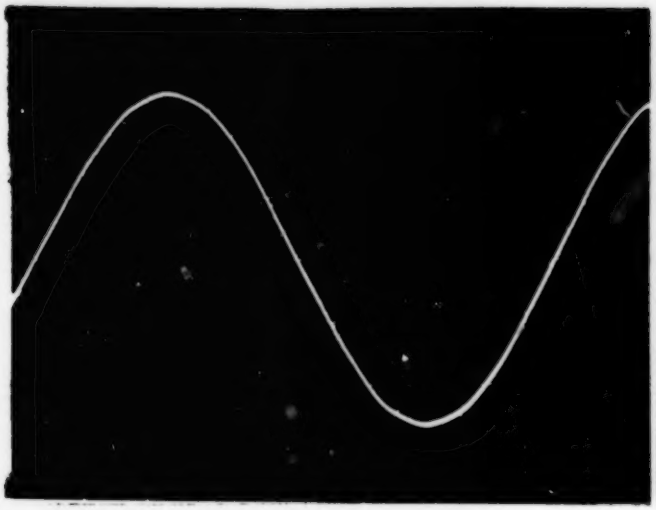
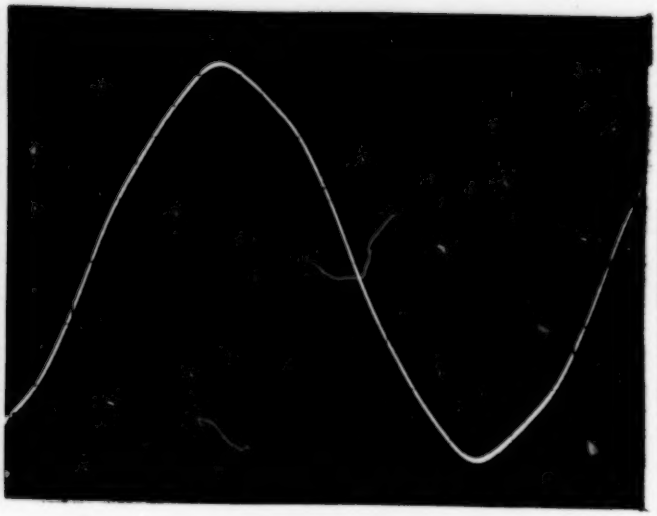
3. IEEE Std 519-1981 "IEEE Guide for Harmonic Control and Compensation of Static Power Converter".

4. Ontario Hydro, Regions Branch Administrative Procedure 2, "Controlling Propagation of Harmonics into the DES by Customers", OOOH, Ser. 2.6, Sec 6.3, Sept 1983.

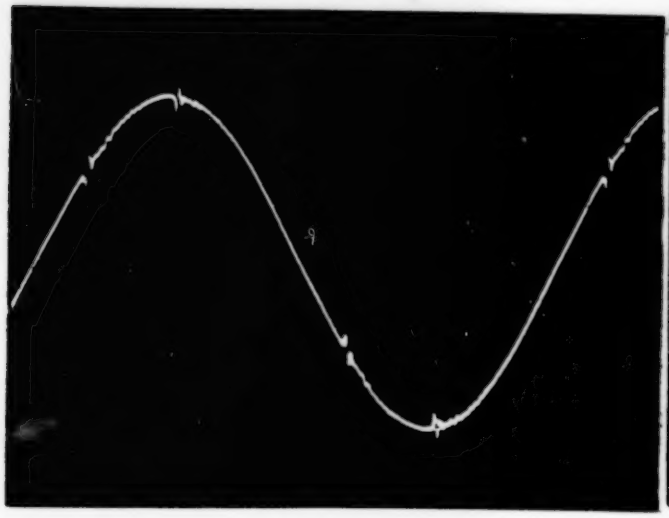


Red Phase Voltage



a) "Off" Cycle

Red Phase Current



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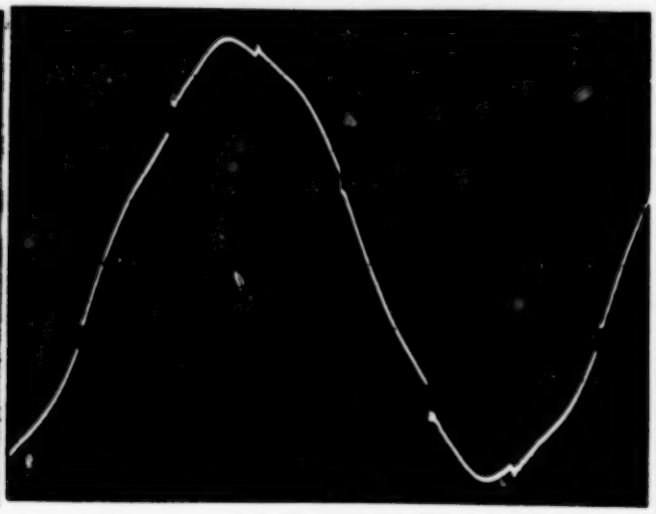
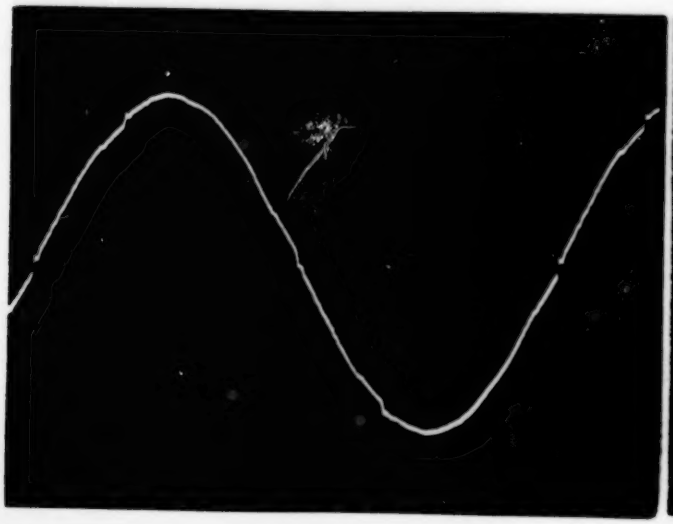
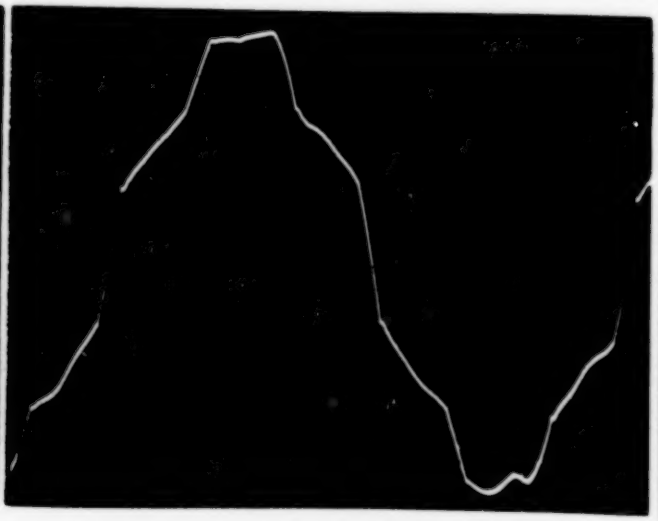


b) "Hold" Cycle

Red Phase Current



Red Phase Voltage



c) "Melt" Cycle

Red Phase Current

Figure 1 Voltage and Current Waveforms at Western Foundry

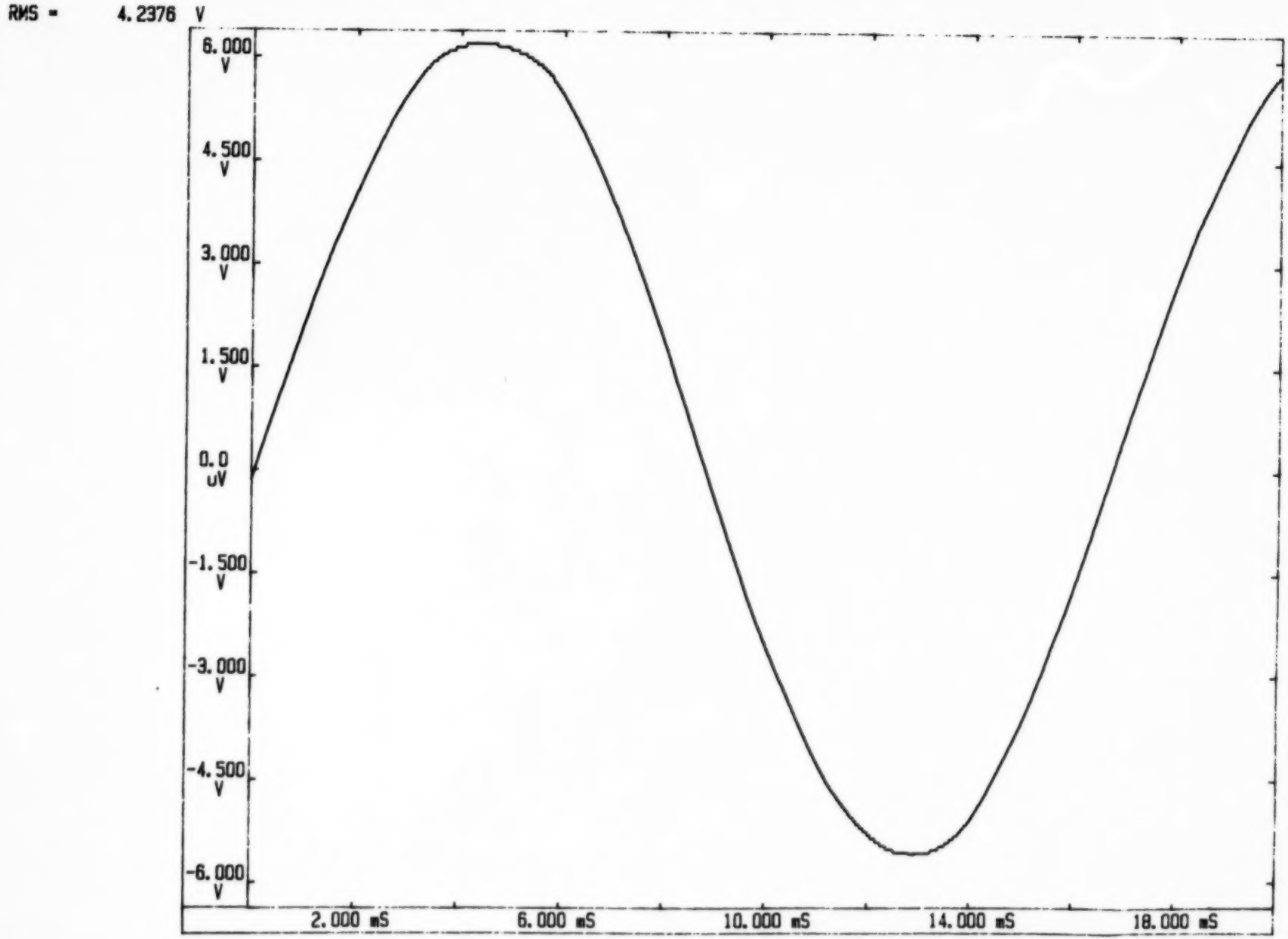


Figure 2 CKNX Voltage Waveform, 120 V ac Supply during "Off" Cycle

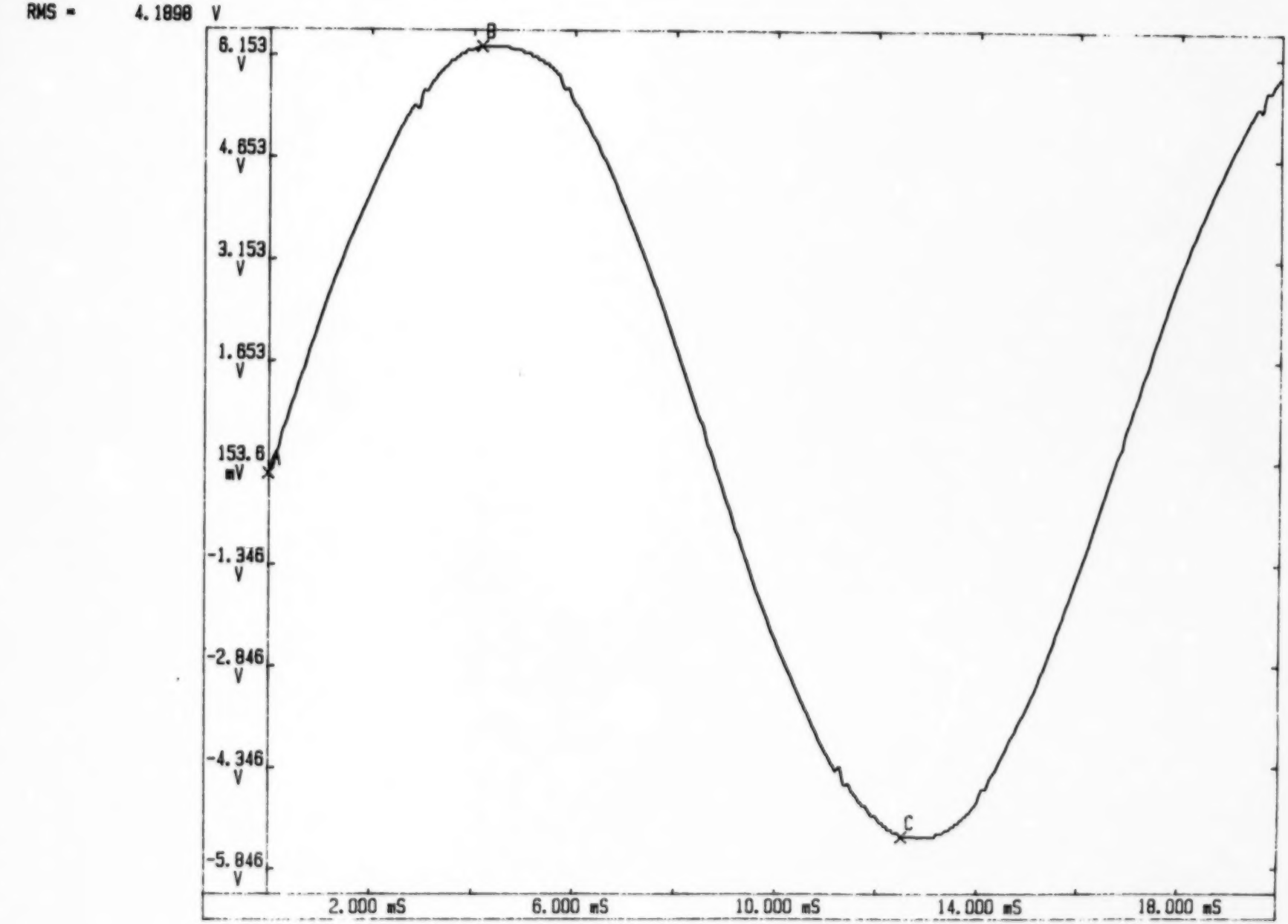


Figure 3 CKNX Voltage Waveform, 120 V ac Supply during "Hold" Cycle

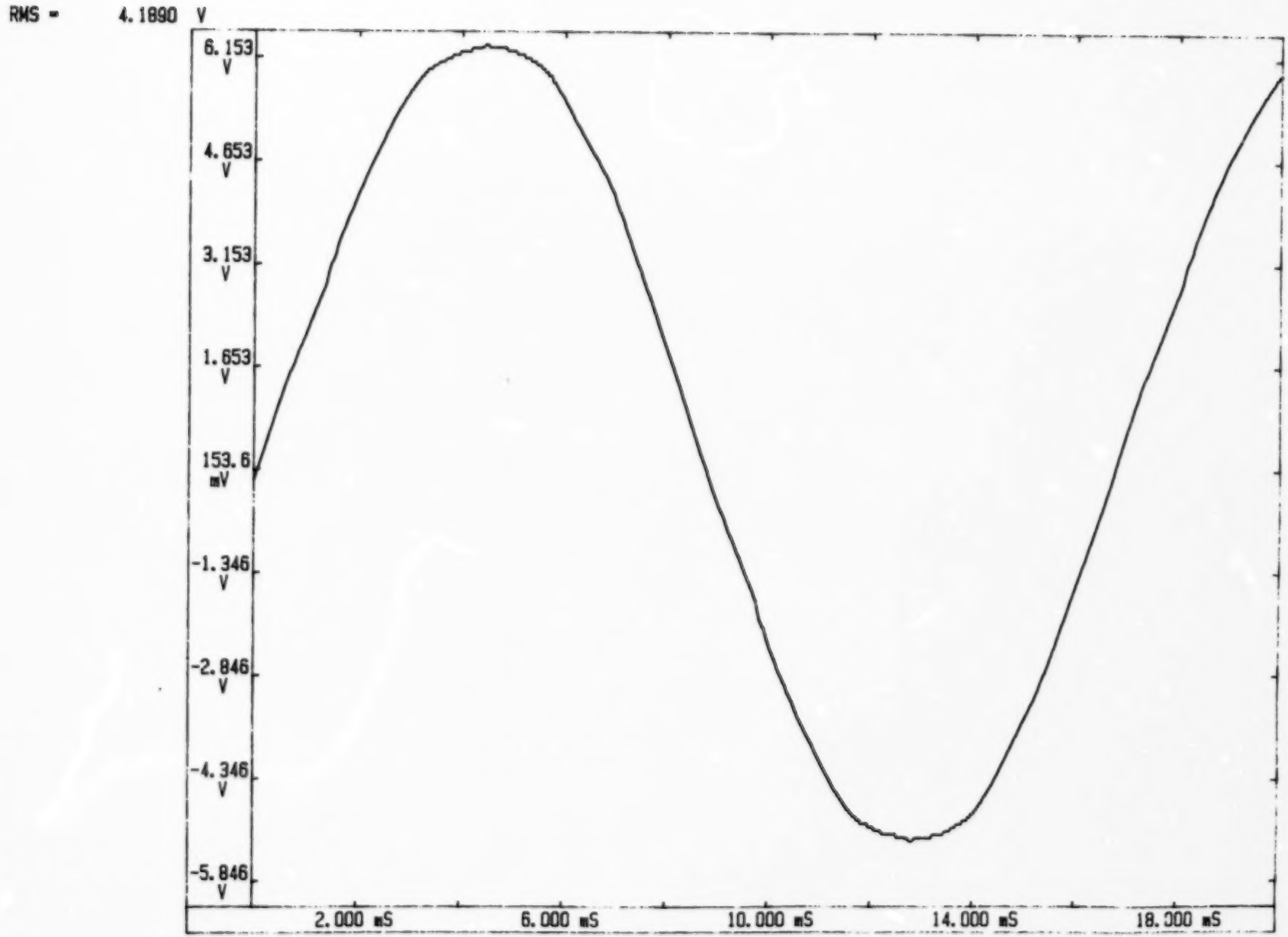


Figure 4 CKNX Voltage Waveform, 120 V ac Supply during "Melt" Cycle

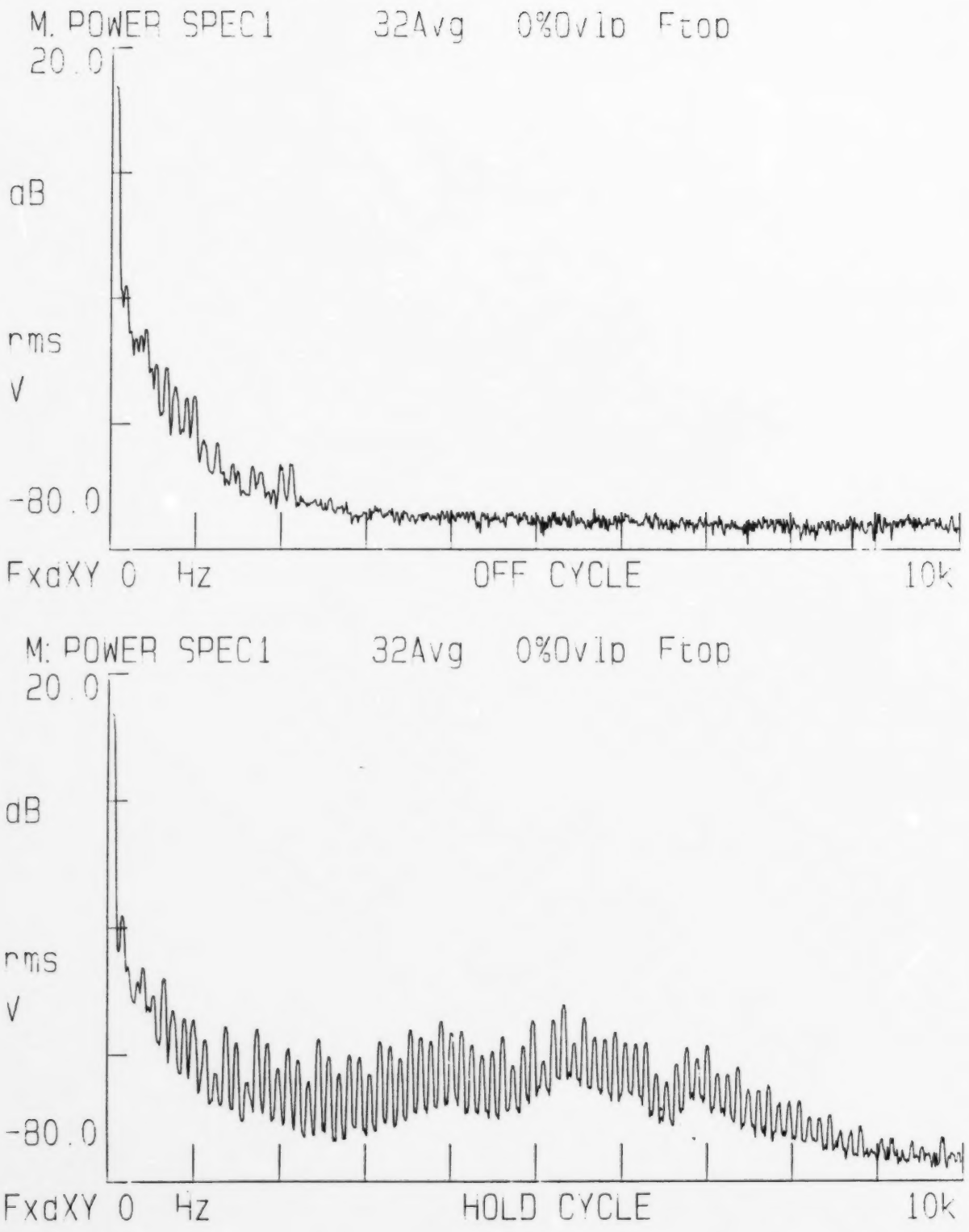


Figure 5 Power Spectra of Voltage Waveform at CKNX, "Off" vs "Hold" Cycles.

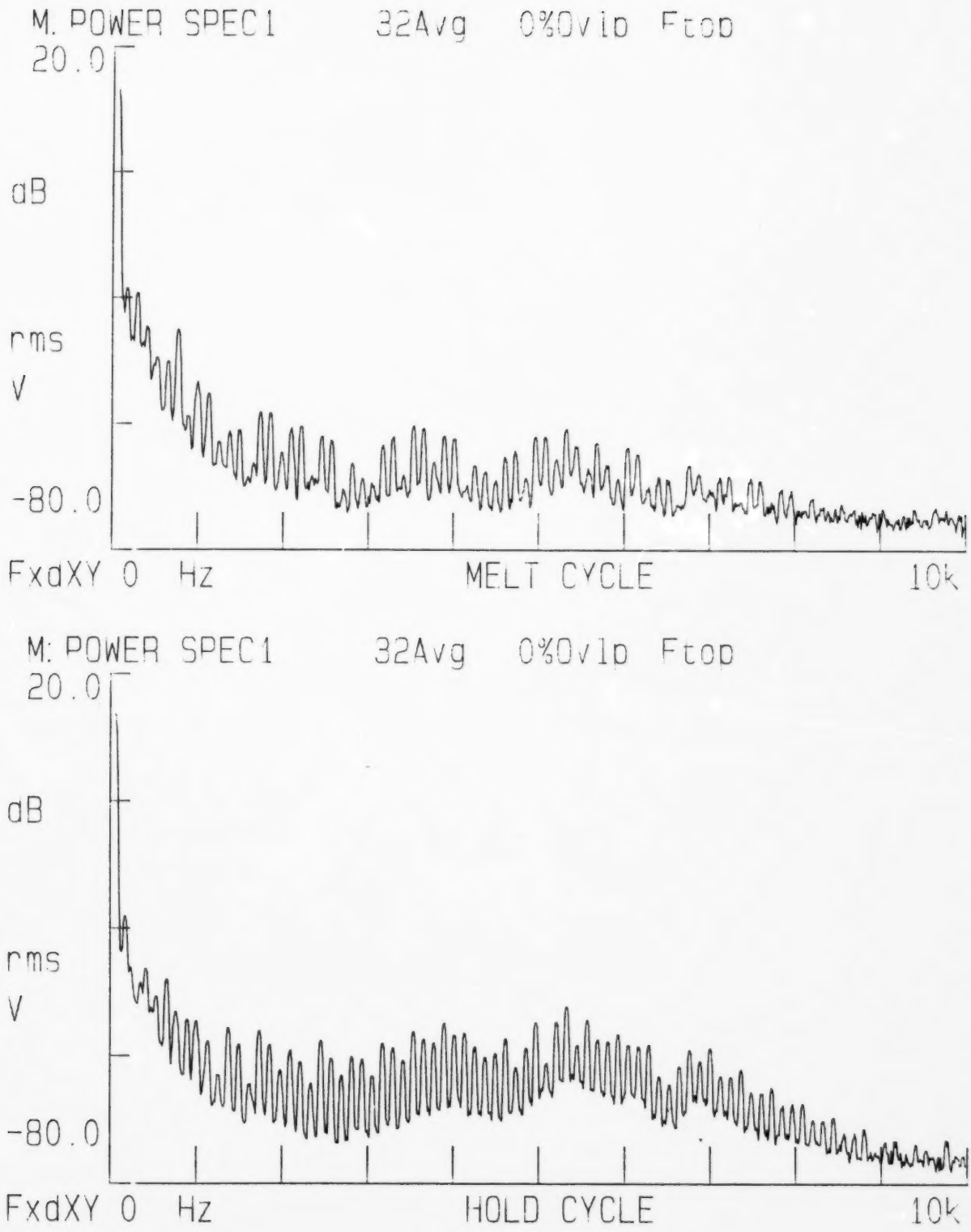


Figure 6 Power Spectra of Voltage Waveform at CKNX, "Melt" vs "Hold" Cycles.